



IMPROVING OPTICAL QUANTUM EFFICIENCY BY CHANGING THE THICKNESS OF CIGS SOLAR CELLS USING NANOTECHNOLOGY SOFTWARE

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<https://doi.org/10.30572/2018/KJE/160332>

ABSTRACT

Nowadays, it is widely recognized that solar PV is one of the favored sustainable energy options globally. Recently, new technological methods have been developed based on the use of thin films and nanostructures with the aim of reducing the solar cell cost and increasing its efficiency. This work includes simulation of Cu(In,Ga)Se₂ nanostructured solar cell. Silvaco program was used with TCAD technology to obtain (ZnO/CdS/CIGS) tandem solar cell model. The thickness of three layers was changed for optical wavelength range (300 –1200) nm, then the optical quantum efficiency was studied and compared with the measured model. The maximum value of quantum efficiency (80%) was obtained when thickness of ZnO layer was doubled, while the maximum value of this efficiency was obtained (74.5%) when reducing the thickness of CdS layer to one-tenth. As for CIGS layer, by increasing its thickness three times, the optimum quantum efficiency obtained is (82.08%). Several peaks are obtained in each case for different values of wavelengths which are determined from (450-750) nm. The best results reached were relied upon to implement an optimal model for a solar cell with several values of maximum efficiency for different wavelengths, as the highest quantitative efficiency (92%) has been achieved.

KEYWORDS

CIGS; Solar cells; Quantum efficiency; Silvaco; Thickness; Wavelength.



1. INTRODUCTION

In recent years, thin film technology had a significant impact on the solar cell industry, especially the CIGS type, as it gave a noticeable improvement in photovoltaic conversion efficiency (Selma & Abdelhalim, 2022, Powalla et al., 2018, Ramanujam & Singhb, 2017). Copper, indium, gallium, and selenium make up the 1-II-V₂ semiconductor material used in thin film CIGS solar cells. They had demonstrated their usefulness in terrestrial applications due to their high efficiency, long-term reliable performance, and cheap production cost being very appealing in the thin film technology market. Actually, polycrystalline solar cells are a good alternative to wafer-based crystalline silicon solar cells, which make up the majority of photovoltaic (PV) systems installed and used globally today (Selma & Abdelhalim, 2022, Powalla & Dimmler, 2000, Reinhard et al., 2013). One of good qualities for Cu(In_{1-x}, Ga_x)Se₂ is that its band gap can be directly adjusted, ranging from 1.0 eV (CuInSe₂) to 1.7 eV (CuGaSe₂), by changing the indium to gallium ratio (Khoshsirat et al., 2015, Touafek & Mahamdi, 2014). One strategy to increase the efficiency of CIGS solar cells is to improve light absorption over a wide range of wavelengths. Ensuring that the CIGS material efficiently absorbs photons across this entire spectrum is a major task (Heriche et al., 2017, Al-Kaoaz & Al-Yozbaky, 2023, Dullweber et al., 2001). With a high absorption coefficient (10^5 cm^{-1}) and an adequate optical band gap, CIGS is a direct semiconductor material, that means that most of the incoming sunlight can be absorbed by CIGS layers as thin as a few micrometers, negating the need for light-trapping structures—which are required in silicon devices (Wada et al., 2001, Powalla et al., 2014). Moreover, ZnO and CdS buffer layers thickness and their composition optimization can enhance the optical characteristics of CIGS solar cells, improve charge carrier extraction, increase light absorption, and function as anti-reflective coatings. To optimize the efficiency and optical wavelength response of CIGS solar cells, simulation tools like those provided by Silvaco are essential (Kadia et al., 2021, El Farri et al., 2021, Menner et al., 2011, Schleussner et al., 2013).

From the output parameters (V_{oc} , I_{sc} , and FF), the most important parameter, power conversion efficiency (PCE or η), can be determined, where the performance of the photovoltaic cell is evaluated. It is defined as the percentage between the maximum electrical power provided by the cell (P_{max}) and the input power from the sun illuminating the cell (P_{in}). On the other hand, quantum efficiency (QE), measures the percentage of photons that are converted into charge carriers (electrons and holes) within (PV) cell (Sim et al., 2018, Vermang et al., 2014).

Power conversion efficiency (PCE) and quantum efficiency (QE) are both important metrics in

evaluating the performance of photovoltaic (PV) cells. Both metrics are important for understanding the performance of photovoltaic cells (Laoufi et al., 2021, Kim & Xu, 2022).

PCE (η) is calculated according to the following formula:

$$\eta = \frac{P_{\max}}{P_{in}} \times 100\% = \frac{I_{mp} \times V_{mp}}{P_{in}} \times 100\% = \frac{FF \times I_{sc} \times V_{oc}}{P_{in}} \times 100\% \quad (1)$$

Conversion efficiency (η) should be improved by increasing the open-circuit voltage (V_{oc}), short-circuit current (I_{sc}), and fill factor (FF).

Also, (QE) may be defined as the ratio of electrons number in the external circuit to the number of incident photons that produce these electrons for a given wavelength. Thus, one can define external and internal quantum efficiencies (denoted by $EQE(\lambda)$ and $IQE(\lambda)$, respectively). All photons impinging on the cell surface are taken into account to calculate EQE but only absorbed photons not reflected are considered for $IQE(\lambda)$.

The following relation gives the external quantum efficiency:

$$EQE(\lambda) = \frac{1}{q} \times \frac{hc}{q} \times \frac{I_{sc}(\lambda)}{P_{in}(\lambda)} \quad (2)$$

Where q is the unit charge, λ is the photon wavelength, h is Planck's constant, c is the light-speed in air, and P_{in} is incident light power. It is worth noting that the EQE spectrum measured under no bias voltage can be used to calculate I_{sc} (I_{ph}). If ($IQE(\lambda)$) is known, the total photo-generated current is given by:

$$I_{ph} = q \int (\lambda) \Phi(\lambda) \{1 - R(\lambda)\} IQE(\lambda) d\lambda \quad (3)$$

where $\Phi(\lambda)$ is the photon flux incident on the cell at wavelength λ , $R(\lambda)$ is the reflection coefficient from the top surface, and the integration is carried out over all wavelength λ of light absorbed by the solar cell. IQE and EQE are measured to evaluate solar cell performance using interference filters or monochromators (Saif et al., 2023, Reinhard et al., 2013, Glowacki et al., 2012).

A Quantum Efficiency is a parameter which describes the performance of an opto-electronic device such as; the solar cells, photodetectors (photodiodes, PD), avalanche photodiodes (APD), charge-couple device (CCD) sensors, and CMOS image sensors (CIS) (Park et al., 2023, Amir, 2008, Omar et al., 2024).

This work aims to improve the photovoltaic quantum efficiency of a CIGS solar cell using nanotechnology by varying the thickness of ZnO/CdS/ CIGS tandem Structure using Silvaco program to simulate the proposed models, where the thickness of each layer is changed and then the efficiency of the solar cell is measured for different optical wavelengths.

2. LITERATURE REVIEW

Numerous investigations have been carried out to optically replicate (EQE) spectra of high-efficiency CIGS-based solar cells, taking into account variations in the CIGS compositional

profile and the thicknesses of different layers that make up the solar cell (Ibdah et al., 2017, Ibdah et al., 2018).

(Jackson et al., 2011), examined the impact of CdS and CIGS thickness on EQE and PV parameters and it was discovered that while all PV and EQE parameters increase with increasing CIGS thickness, they decrease with increasing CdS thickness.

(Tobbeche & Amar, 2014), performed a simulation of a CIGS solar cell operating under AM 1.5 illumination using Silvaco Atlas software. It has been demonstrated that a crucial tool for understanding and producing highly efficient CIGS solar cells is numerical modeling. In addition to offering a clear understanding of predicting potential efficiency improvements using numerical calculations. The CIGS solar cell's modeling yielded an efficiency of 20.35 percent, which agrees well with the standard high recorded efficiency of 20.3 percent.

(Firoozi & Imanieh, 2018), presented a study on the function of solar cells with a $\text{CuIn}_{1-x}\text{Ga}_x\text{Se}_2$ structure where the cell layers were; ZnO, CdS, CIGS (absorbent layer), and MO layer (substrate). A PN connection was established between CdS and CIGS layers. After that, they designed and simulated the solar cell using the SILVACO program, then adjusted the thickness of CdS layer and studied the behavior of this solar cell.

(Khadir, 2020), found that the conversion efficiency (CE) significantly decreased as the thickness of each window or buffer layer increased. Also, increasing the thickness of absorbent layer increases the (CE) significantly. In addition to reducing the thickness of each layer, interesting ideal parameters were found to bring (CE) closer to the experimental value. According to his findings, the optimal structure has a 20.64% conversion efficiency and thicknesses of 0.11 μm for MgF_2 , 10^{14} cm^{-3} donor defects density in CIGS, and 0.25, 0.06, 0.03, and 1.6 μm for ZnO: Al, I-ZnO, CdS, and CIGS, respectively.

(Ahmed et al., 2022), studied approaches for determining the maximum power point based on photovoltaic system disturbance. A comparative study of the methodologies is performed. The operation of a solar battery under partial shade is considered a challenge in tracking the maximum power point, and solutions to this problem are explored using MATLAB/Simulink. Modeling and simulation provide a good service for researchers to know the work nature of various photovoltaic devices before manufacturing them and study their characteristics. (Selma & Abdelhalim, 2022, Bouchama et al., 2011).

(Raad and Nabil, 2024) cooled the solar cell using fins as heat sinks placed behind the cell. They then compared the performance of such cells with the performance of other air-cooled solar cells, where it was found that the used fins reduced the cell temperature and thus improved its electrical and thermal efficiency.

The difference between this research paper and others is that the positive effect of increasing the thickness of the ZnO layer on the quantum efficiency of the solar cell is greater than decreasing its thickness. In addition, the thickness of the CIGS absorber layer was increased to only 1.08 micrometers to obtain the highest efficiency, which is (82.08%), which was not achieved previously, as the thickness of this layer reached 2 microns. In addition to what was mentioned, the best proposed model was obtained, through which the highest quantitative efficiency (92%) was obtained.

In this work, a new approach was adopted to compare with previous works, through which the lowest thickness (lowest cost) and highest efficiency were obtained, in addition to deducing a proposed model that includes all the optimal cases for all layers composing the solar cell, not to mention focusing on the optimal optical wavelengths to obtain the best efficiency.

3. PRACTICAL SIMULATION AND RESULTS

The proposed methodology was determined on the rationale, which is to take the measured thickness of the solar cell layers with the corresponding QE for a specific optical wavelength, then start increasing the thickness of each layer and observe the change in QE, then start decreasing the thickness and observe the difference between the increase and decrease for a specific wavelength, then conclude which has a more positive effect on the cell efficiency, and finally design an optimal model with the highest possible efficiency for different wavelengths.

3.1. Modeling Structure

2D Silvaco program was used with TCAD technology to obtain ZnO/ CdS/ CIGS triple-layer tandem solar cell model with thicknesses; 440 nm, 40 nm, 360 nm and (300 nm) Mo as substrate layer respectively on glass substrate. The materials used in the formation of this model and the electrodes ports of cathode and anode are specified in Fig. 1 below (Amir et al., 2024, Naqaa et al., 2020).

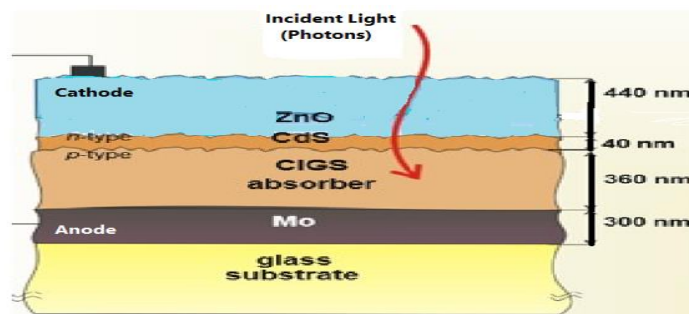


Fig. 1. Tandem solar cell structure of ZnO/CdS/CIGS.

Atlas module enabled the implementation of simulations for the design of semiconductor-based photovoltaic devices and study their characteristics. Fig. 2, illustrates the simulated quantum efficiency with respect to measured model for different optical wavelengths, where the match

seemed clear between the two curves especially at the optimal value (72.8%) which occurred at optical wavelength (530 nm).

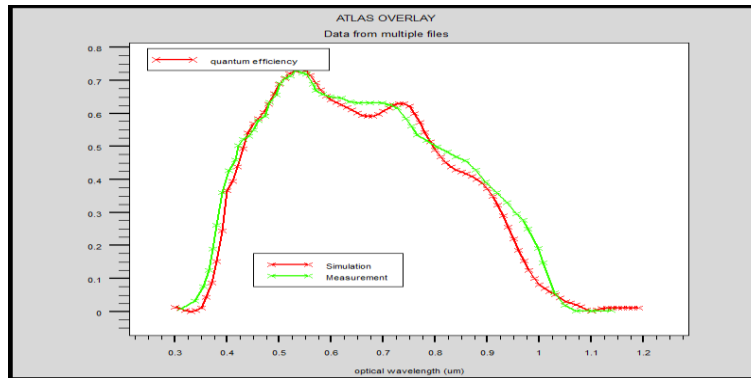


Fig. 2. Comparison of quantum efficiency versus optical wavelength for the measured and simulated model.

3.2. Results Analysis and Discussion

In this work, a nanostructured CIGS solar cell is simulated, for the purpose of improving its performance and then increasing its quantum efficiency. In order to achieve this goal, the thickness of three layers forming the solar cell was changed individually.

3.2.1. ZnO-layer results

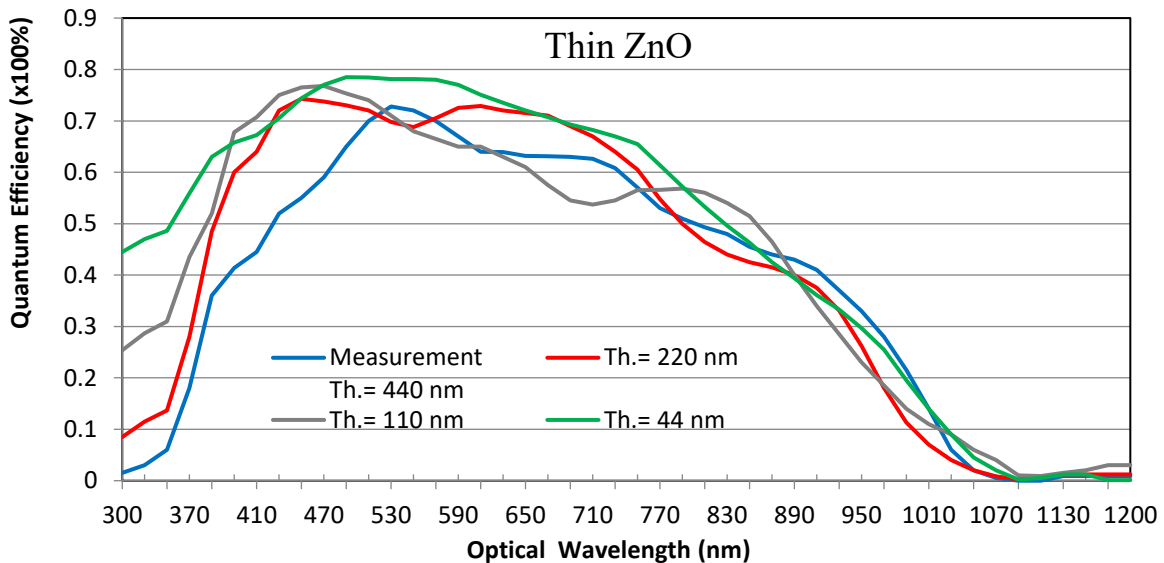
The thickness of ZnO layer was continuously reduced until reaching one-tenth, where a clear improvement in (QE) value was observed, but the results were not at the desired level. After that, the thickness was doubled to see a clear improvement in the performance of the solar cell, represented by a noticeable increase in (QE) value, as shown in [Table 1](#) below:

Table 1. Maximum quantum efficiency values with optical wavelengths for different thicknesses of ZnO layer.

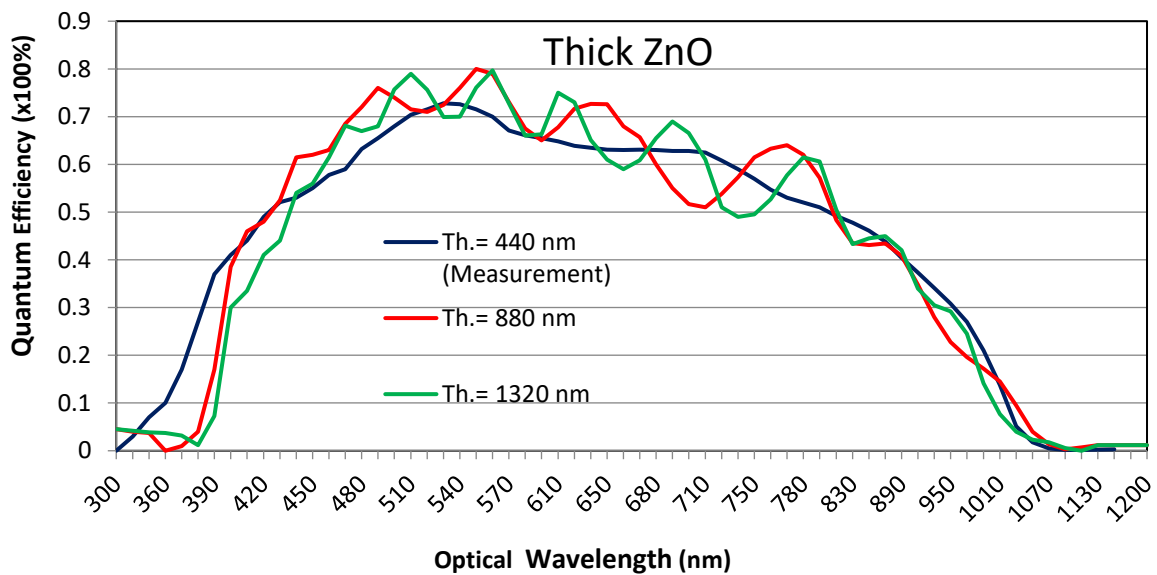
Optical Wavelength (nm)	Quantum Efficiency (%)					
	Thickness					
	44 (nm)	110 (nm)	220 (nm)	440 (nm)	880 (nm)	1.32(μm)
450			74.3			
470		76.8				68.1
490	78.5				76	
510						79
530				72.8		
550					80	
560						79.7
610			72.9			75
640					72.7	
690						69
780						61.5
790		56.8				
870						45

[Fig. 3](#) shows the changing of (QE) with optical wavelength for thin and thick ZnO Layers. A maximum value of efficiency (78.5%) was obtained at a wavelength of (490 nm) when the

thickness was reduced to a tenth, while the improvement in efficiency increased significantly when the thickness was doubled to reach (80%) at a wavelength of (550 nm) with fluctuation in efficiency and thus obtaining multi-peaks at different wavelengths.



(a)



(b)

Fig. 3. Variation of quantum efficiency with optical wavelength for:
(a) Thinner ZnO layers. (b) Thicker ZnO layers.

3.2.2. CdS-layer results

Secondly, the thickness of CdS layer was reduced continuously until it reached one-tenth, then a slight improvement in (QE) was obtained. On the other hand, increasing the thickness gave undesirable results, this is shown in Table 2 below:

Fig. 4 shows the (QE) variation with optical wavelength for thin and thick CdS Layers. A maximum value of efficiency (74.5%) at a wavelength of (510 nm) was obtained when the

thickness was reduced from (40 nm) to (4 nm), and this means consuming less materials for manufacturing and a shorter time for deposition. On the contrary, the results are disappointing when the thickness of this material is doubled once as well as twice, noting that the fluctuation of curves in all cases increased to reach 3 peaks or more, which will give different values for the (QE) response with multiple wavelengths, but with lower efficiency.

Table 2. Maximum quantum efficiency values with optical wavelengths for different thicknesses of CdS layer.

Optical Wavelength (nm)	Quantum Efficiency (%)					
	Thickness (nm)					
	4	10	20	40	80	120
430	53.7	53.1				
440			51.8			
490					65	
510	74.5	73.9				69.2
520			72.2			
530				72.8		
590					66.2	
630						67.4
690	66.1	65.2				
710			63.9			
770					57	
810						51.8
850	42.7	42.4				

3.2.3. CIGS-layer results

The thickness of the CIGS was reduced by half, but no significant results were obtained, while when starting to increase the thickness, a clear improvement in (QE) was observed, especially when the thickness exceeded (1) micrometer, as shown in [Table 3](#) below:

Table 3 Maximum Quantum Efficiency Values with Optical Wavelengths for Different Thicknesses of CIGS Layer.

Optical Wavelength (nm)	Quantum Efficiency (%)					
	Thickness					
	180 (nm)	270 (nm)	360 (nm)	540 (nm)	720 (nm)	1.08 (μm)
530			72.8			
540	52.3	67.85		78.05		
550					80.18	82.08
640		57.7				
680	46.61					
690						
700				71.08		
730					76.16	81.43
750		53.94				
930					41.9	
960						43.57

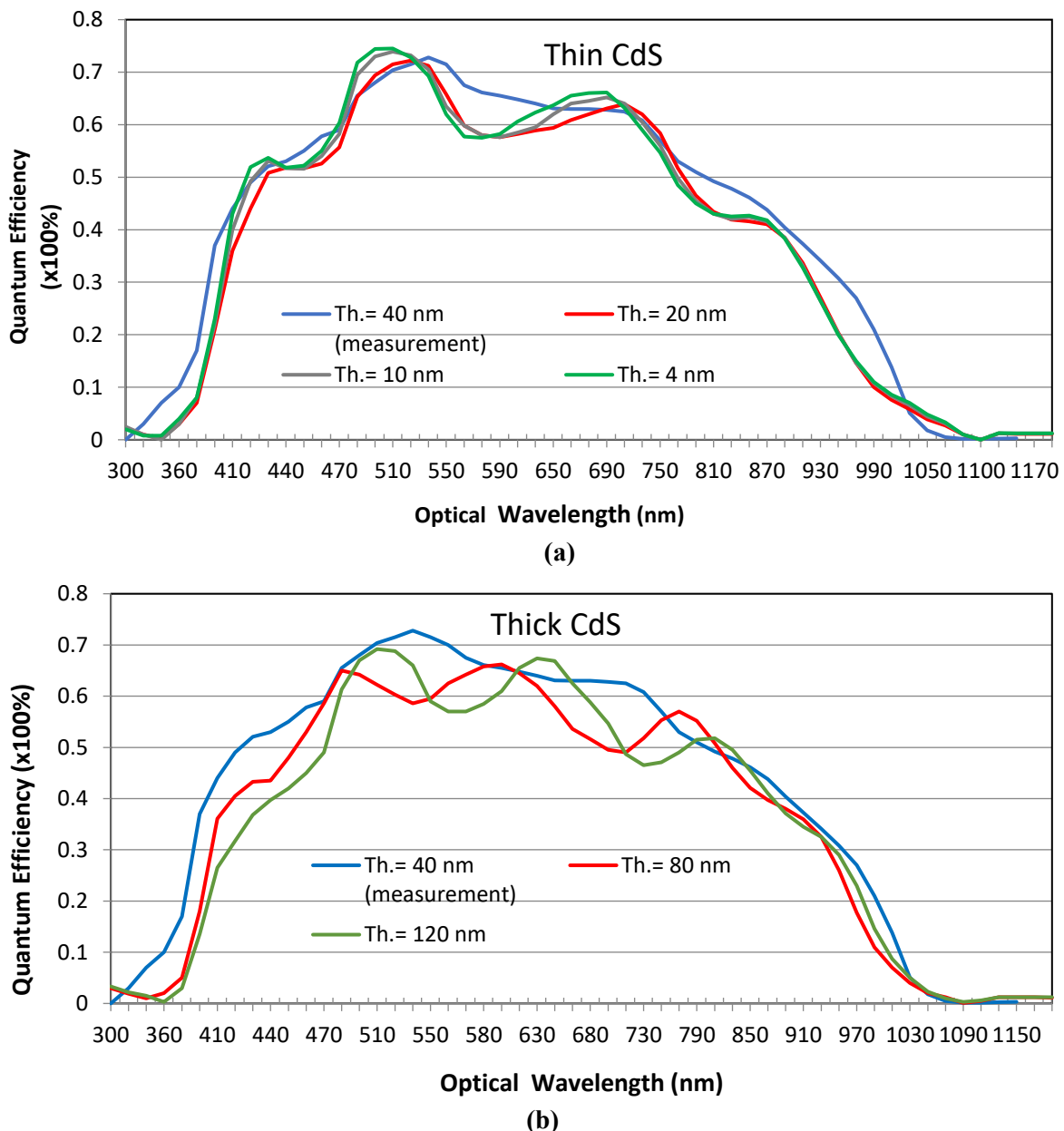
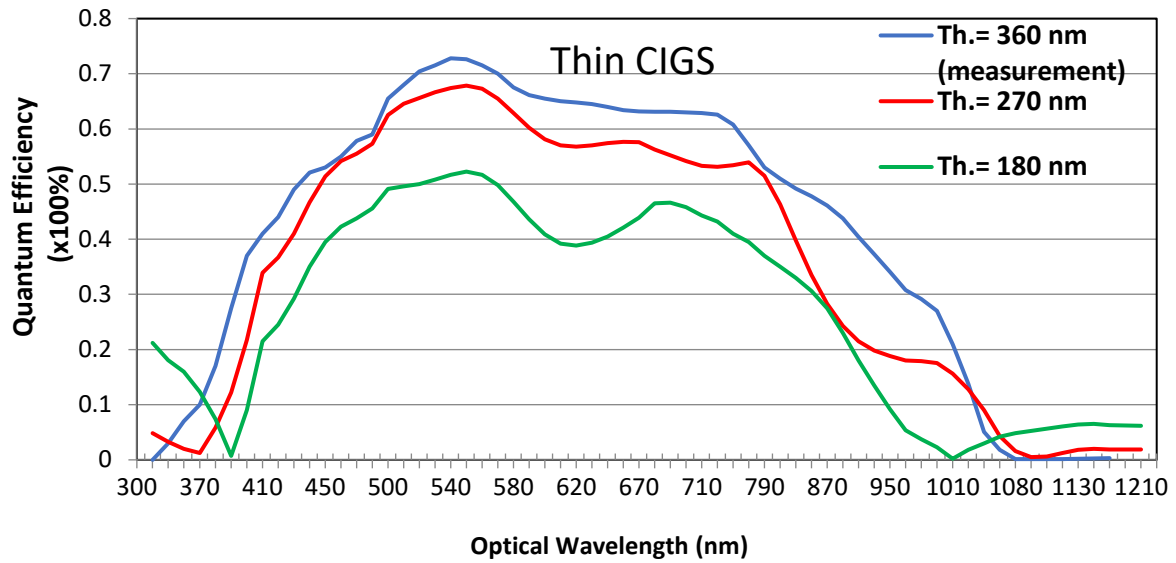


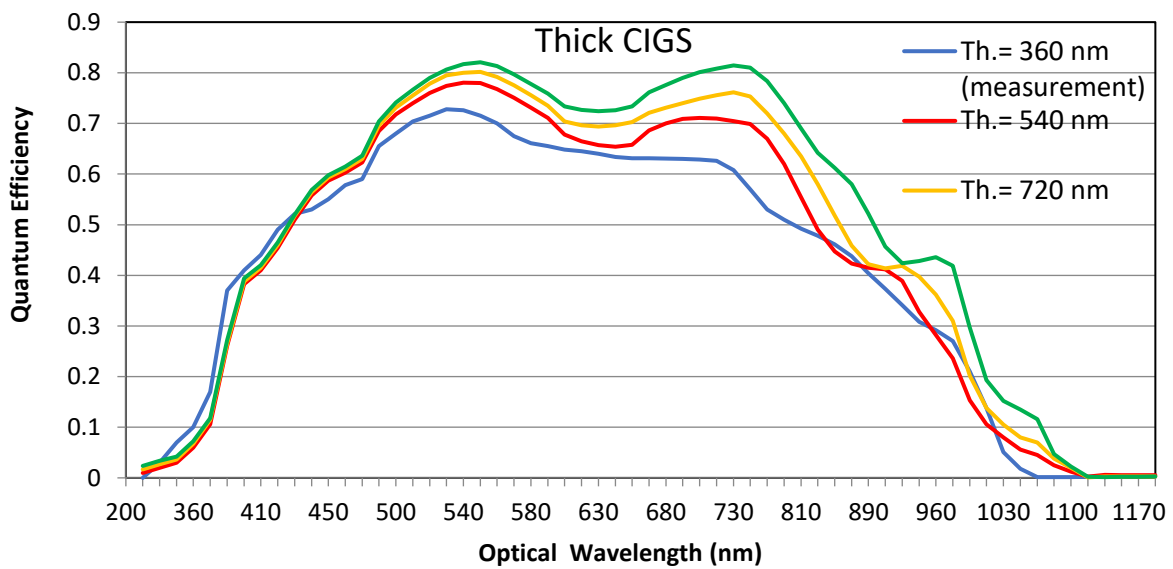
Fig. 4. The quantum efficiency as a function of optical wavelength for
(a) Thinner CdS layers. (b) Thicker CdS layers.

By observing Fig. 5, it appears that reducing the thickness of the CIGS layer yields bad results. While in the case of increasing it, there will be a significant increase in the QE value to reach its optimum value (82.08%) at the wavelength of incident light (550 nm). This is what happened when the thickness reached to 1.08 μm (i.e. tripling the original thickness).

Also, a maximum value of QE close to the optimal value was obtained, which is (81.43%), but at an optical wavelength of (730 nm). These results lead to an important and useful conclusion in practical applications, which is that this solar cell can absorb more than one wavelength and operate with almost the same efficiency.



(a)



(b)

Fig. 5. The quantum efficiency vs. optical wavelength for: (a) Thinner CIGS layers. (b) Thicker CIGS layers.

3.3. Quantum Efficiency Peaks Charts

All the results reached were collected in one chart for each layer and all thicknesses. Fig. 6 indicates peaks chart for ZnO layer from (44 - 1320) nm thickness. While Fig. 7 shows peaks chart for CdS layer from (4-120) nm thickness. As for Fig. 8, it indicates the peaks chart for the most important and effective layer, which is the acceptor CIGS layer from (180-1080) nm thickness, where the efficiency is highest. All previous figures were drawn in terms of different wavelengths.

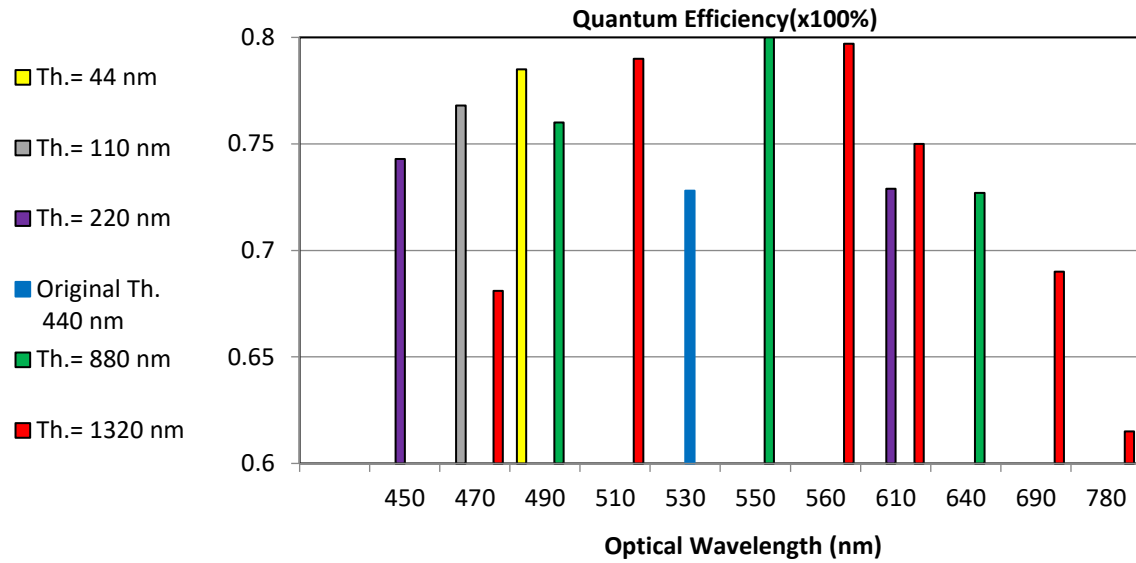


Fig. 6. Quantum efficiency peaks chart of ZnO for different thicknesses.

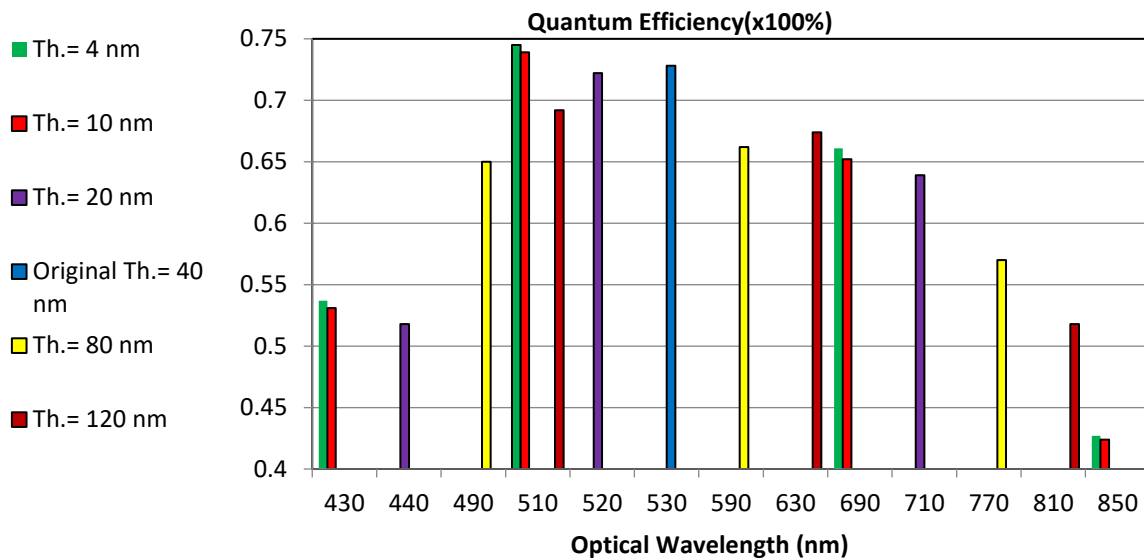


Fig. 7. Quantum efficiency peaks chart of CdS for different thicknesses.

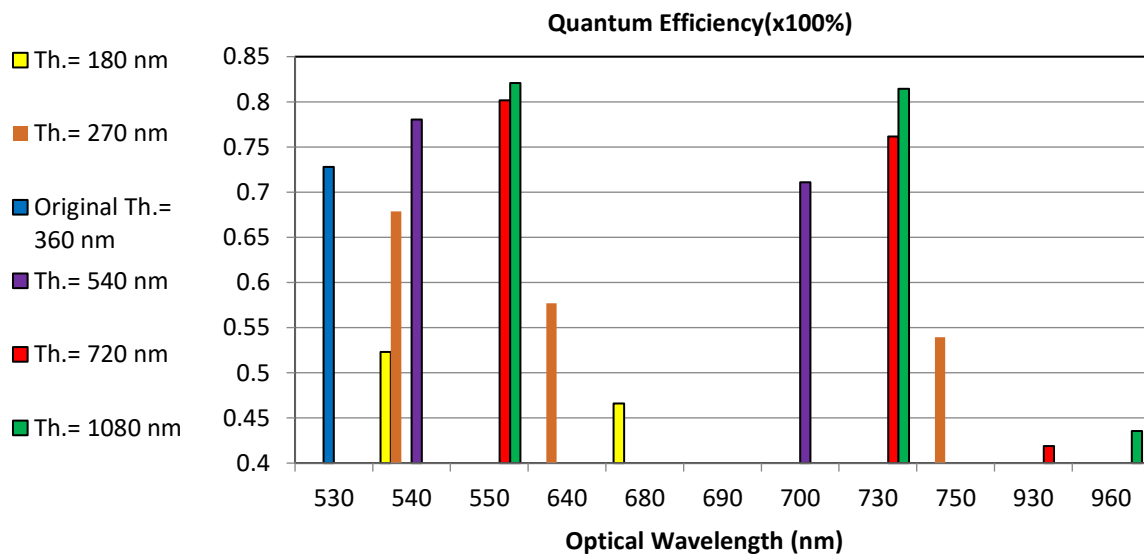


Fig. 8. Quantum efficiency peaks chart of CIGS for different thicknesses.

3.4. Proposed Model

The better quantitative efficiency illustrated in Fig. 9, where the best results obtained during the research were taken into account, and then they were applied in one program, where the thicknesses of the three layers were (ZnO/CdS/CIGS) are (880, 4 and 1080) nm, respectively. Impressive results were obtained, represented by optimal values of QE (92%, 90.9%, and 85.8%) at optical wavelengths of (530, 620, and 750) nm, respectively. In addition, four less intense peaks appeared at different wavelengths.

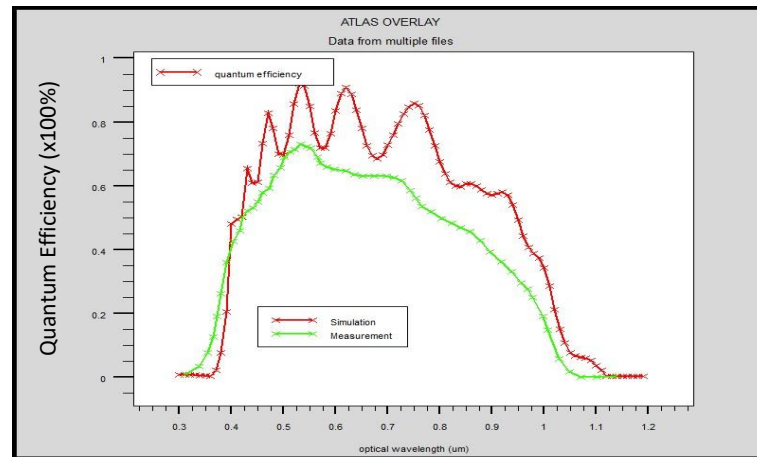


Fig. 9. The best model of quantum efficiency for different wavelengths.

In short, the most important results obtained through this research that distinguished this work from previous works is obtaining a near-ideal model for a CIGS solar cell with a quantum efficiency of 92%, in addition to having maximum responses at lower values for multiple optical wavelengths as shown in Fig. 9 above. Table 4 shows the results of this work compared to other works.

Table 4: A comparison between the previous researches and the current research.

Reference	Methodology	Results
Jackson et al., 2011	The effect of CdS and CIGS thickness on EQE and PV parameters was examined.	While all PV and EQE parameters increase with increasing CIGS thickness, they decrease with increasing CdS thickness.
Tobbeche & Amar, 2014	A simulation of a CIGS solar cell operating under AM 1.5 illumination was performed using Silvaco Atlas software.	Modeling of the CIGS solar cell yielded an efficiency of 20.35 percent, which is in good agreement with the record efficiency.
Firoozi & Imanieh, 2018	Design and simulation of CIGS solar cell using SILVACO software and then study the function of the layered cell; ZnO, CdS and CIGS after changing the CdS layer thickness	Changing the thickness of CdS layer had a great effect on the function of solar cell especially external efficiency.

Reference	Methodology	Results
Khadir, 2020	CIGS based solar cell structure has been carried out using Atlas module from SILVACO tech., varying the thickness of each layer and optimizing the anti-reflective coating (ARC) layer. JSC, VOC, FF, and conversion efficiency (η) were calculated.	The optimal thicknesses of 0.11, 0.25, 0.03, and 1.6 μm for ARC, ZnO, CdS, and CIGS layer, respectively, give a conversion efficiency of 20.64%.
Raad & Nabeel, 2024	Using fins mounted on the back surface of the solar panel for passive cooling and comparing air-cooled solar modules with modules with attached fins.	Reduced the cell temperature and improved the electrical and thermal efficiency, with the largest increases in electrical and thermal efficiency (16.54% and 58.3%, respectively).
The current Research	This work aims to improve the photovoltaic quantum efficiency of a CIGS solar cell using nanotechnology by varying the thickness of ZnO/CdS/CIGS tandem Structure using Silvaco program to simulate the proposed models, where the thickness of each layer is changed and then the efficiency of the solar cell is measured for different optical wavelengths.	An optimal proposed model for the CIGS solar cell with multiple maximum quantum efficiencies was deduced at different optical wavelengths, obtaining the highest efficiency (92%) with the smallest thickness (lowest cost).

4. CONCLUSIONS

The changing of layer thickness had a significant impact on the performance of CIGS solar cell, as it was found that reducing the thickness of reflective CdS layer, positively affects the quantum efficiency of this cell, as the highest quantum efficiency (74.5%) was obtained, while increasing the thickness of ZnO layer has a greater positive effect, where this efficiency reached (80%). As for the most important layer (the absorber CIGS layer), the improvement was more evident than the other layers with increasing the thickness, as the quantum efficiency reached its maximum value (82.08%) at an optical wavelength of (550) nm, which occurred when the thickness was tripled. This promising and impressive increase in QE has led to the concept that CIGS has a great ability to convert light energy into electrical energy and thus improve the performance of solar cell. Also, the highest peaks of quantitative efficiency were obtained when the optimum values of thickness were applied programmatically, and the best result was (92%). These results lead to an important and useful conclusion in practical applications, as this type of solar cell can absorb more than one wavelength at the same time, with close efficiency values. The effective wavelength range that gives the highest quantum efficiency is from (450 to 750) nm. As future work, and based on the promising results obtained and in continuation of the research approach, it is possible to combine optical and electrical analysis of the tandem solar cell so that the study will be broader and more comprehensive.

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